Keplerian Motion of Broad-Line Region Gas as Evidence for Supermassive Black Holes in Active Galactic Nuclei

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ABSTRACT

Emission-line variability data on NGC 5548 argue strongly for the existence of a mass of order $7 \times 10^7 \, M_\odot$ within the inner few light days of the nucleus in the Seyfert 1 galaxy NGC 5548. The time-delayed response of the emission lines to continuum variations is used to infer the size of the line-emitting region, and these determinations are combined with measurements of the Doppler widths of the variable line components to estimate a virial mass. The data for several different emission lines spanning an order of magnitude in distance from the central source show the expected $V \propto r^{-1/2}$ correlation and are consistent with a single value for the mass.

Subject headings: galaxies: active — galaxies: individual (NGC 5548) — galaxies: quasars: emission lines — galaxies: Seyfert

1. Introduction

From the earliest days of quasar research, supermassive black holes (SBHs) have been considered to be a likely, if not the most likely, principal agent of the activity in these sources. Evidence for the existence of SBHs in active galactic nuclei (AGNs), and indeed in non-active nuclei as well, has continued to accumulate (e.g., Kormendy & Richstone 1995). In the specific case of AGNs, probably the strongest evidence to date for SBHs has been Keplerian motions of megamaser sources in the Seyfert galaxy NGC 4258 (Miyoshi et al. 1995) and asymmetric Fe Kα emission in the X-ray spectra of AGNs (e.g., Tanaka et al. 1995), though the latter is still somewhat controversial as the origin of the Fe Kα emission has not been settled definitively.

The kinematics of the broad-line region (BLR) potentially provide a means of measuring the central masses of AGNs. A virial estimate of the central mass, $M \approx r\sigma^2/G$, can be made by using the line velocity width σ, which is typically several thousands of kilometers per second, and the

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size of the emission-line region r. For this to be meaningful, we must know that the BLR gas motions are dominated by gravity, and we must have some reliable estimate of the BLR size. The size of the BLR can be measured by reverberation mapping (Blandford & McKee 1982), and this has been done for more than two dozen AGNs. Whether or not the broad emission-line widths actually reflect virial motion is still somewhat problematic: while the relative response time scales for the blueshifted and redshifted wings of the lines reveal no strong signature of outflow, there are still viable models with non-gravatitionally driven cloud motions. However, if the kinematics of the BLR can be proven to be gravitationally dominated, then the BLR provides an even more definitive demonstration of the existence of SBHs than megamaser kinematics because the BLR is more than two orders of magnitude closer to the central source than the megamaser sources. Recent investigations of AGN virial masses estimates based on BLR sizes have been quite promising (e.g., Wandel 1997; Laor 1998) and suggest that this method ought to be pursued.

In this Letter, we argue that the broad emission-line variability data on one of the best-studied AGNs, the Seyfert 1 galaxy NGC 5548, demonstrates that the BLR kinematics are Keplerian, i.e., that the emission-line cloud velocities are dominated by a central mass of order $7 \times 10^7\,M_\odot$ within the inner few light days ($r \lesssim 5 \times 10^{15}$ cm). We believe that this strongly supports the hypothesis that SBHs reside in the nuclei of active galaxies.

2. Methodology

Measurement of virial masses from emission lines requires (1) determination of the BLR size, (2) measurement of the emission-line velocity dispersion, and (3) a demonstration that the kinematics are gravitationally dominated. A correlation between the BLR size and line-width of the form $r \propto \sigma^{-2}$ could be taken as evidence for point (3), although there are other perhaps contrived situations that could mimic such a correlation. For gravitationally dominated dynamics, the size–line-width relationship must hold for all lines at all times. Indeed, the absence of such a relationship has been regarded as the missing item in AGN SBH measurements (Richstone et al. 1998).

Here we consider the case of NGC 5548, which has been the subject of extensive UV and optical monitoring campaigns by the International AGN Watch consortium[1] (Alloin et al. 1994) for more than ten years. The data are from UV monitoring programs undertaken with the *International Ultraviolet Explorer (IUE)* in 1989 (Clavel et al. 1991) and with *IUE* and *Hubble Space Telescope (HST)* in 1993 (Korista et al. 1995), plus ground-based spectroscopy from 1989 to 1996 (Peterson et al. 1999 and references therein). We consider the response of a variety of lines in two separate observing seasons (1989 and 1993) and the response of Hβ over an eight-year period.

[1]Information about the International AGN Watch and copies of published data can be obtained on the World-Wide Web at URL http://www.astronomy.ohio-state.edu/~agnwatch/.

Cross-correlation of the continuum and emission-line light curves yields a time delay or "lag" that is interpreted as the light-travel time across the BLR. Specifically, the centroid of the cross-correlation function (CCF) $\tau_{\rm cent}$ times the signal propagation speed c is the responsivity-weighted mean radius of the BLR for that particular emission line (Koratkar & Gaskell 1991).

We have measured $\tau_{\rm cent}$ for various emission lines using light curves of NGC 5548 in the AGN Watch data base and the interpolation cross-correlation method as described by White & Peterson (1994). The UV measurements for 1989 are the GEX values from Clavel et al. (1991). The UV measurements for 1993 are taken from Tables 12–14 and 16–17 of Korista et al. (1995). The optical data for 1989–1993 are from Wanders & Peterson (1996) and from Peterson et al. (1999) for 1994–1996. Uncertainties in these values were determined as described by Peterson et al. (1998b). The results are given in Table 1, in which columns (1) and (2) give the epoch of the observations and the emission line, respectively. Column (3) gives the lag $\tau_{\rm cent}$ and its associated uncertainties.

Emission-line widths are not simple to measure on account of contamination by emission from the narrow-line region, and in some cases, contamination from other broad lines. We have circumvented this problem by using a large number of individual spectra to compute mean and root-mean-square (rms) spectra, and we measure the width of the emission features in the rms spectrum. The advantage of this approach is that constant or slowly varying components of the spectrum do not appear in the rms spectrum, and the emission features in the rms spectrum accurately represent the parts of the emission line that are varying, and for which the time delays are measured (Peterson et al. 1998a). This technique requires very homogeneous spectra: for the 1989 UV spectrum, we used the GEX-extracted SWP spectra. For the 1993 UV spectrum, we used the *HST* FOS spectra, excluding those labeled "dropouts" by Korista et al. (1995) which were not optimally centered in the FOS aperture. For the optical spectra through 1993, we used the homogeneous subset analyzed by Wanders & Peterson (1996), and a similar subset for 1994–1996. In each rms spectrum, we determined the full-width at half-maximum (FWHM) of each measurable line, with a range of uncertainty estimated by the highest and lowest plausible settings of the underlying continuum. The line widths are given as line-of-sight Doppler widths in kilometers per second in column (4) of Table 1.

Each emission line provides an independent measurement of the virial mass of the AGN in NGC 5548 by combining the emission-line lag with its Doppler width in the rms spectrum. Column (5) of Table 1 gives a virial mass estimate $M = f r_{\rm BLR} \sigma_{\rm rms}^2/G$ for each line, where $\sigma_{\rm rms} = \sqrt{3}V_{\rm FWHM}/2$ (Netzer 1990) and $r_{\rm BLR} = c\tau_{\rm cent}$. The factor f depends on the details of the geometry, kinematics, and orientation of the BLR, as well as the emission-line responsivity of the individual clouds, and is expected to be of order unity. Uncertainty in this factor limits the accuracy of our mass estimate to about an order of magnitude (see §3). Neglecting the systematic uncertainty in f, the unweighted mean of all these mass estimates is $6.8\,(\pm 2.1) \times 10^7\,M_\odot$. To within the quoted uncertainties, all of the mass measurements are consistent. The large systematic uncertainty should not obscure the key result, namely that the quantity $r_{\rm BLR}\sigma_{\rm rms}^2/G$ is constant and argues strongly for a central mass of order $7 \times 10^7\, M_\odot$.

In Fig. 1, we show the measured emission-line lag $\tau_{\rm cent}$, plotted as a function of the width of the line in the rms spectrum for various broad emission lines in NGC 5548. Within the measurement uncertainties, all the lines yield identical values for the central mass. A weighted fit to the relationship $\log(\tau_{\rm cent}) = a + b \log(V_{\rm FWHM})$ yields $b = -1.96 \pm 0.18$, consistent with the expected value $b = -2$, although the somewhat high reduced χ^2_ν value of 1.70 (compared with $\chi^2_\nu = 2.14$ for a forced $b = -2$ fit as shown in the figure) suggests that there may be additional sources of scatter in this relationship beyond random error.

If our virial hypothesis is indeed correct, we should measure the same mass using independent data obtained at different times. The Hβ emission line in NGC 5548 is the only line for which reverberation measurements have been made for multiple epochs. In Fig. 2a, we show the measured Hβ lag as a function of the width of the Hβ line in the rms spectrum for the six years listed in Table 1. The relationship is shallower than that seen in the multiple-line data shown in Fig. 1 ($b = -0.72 \pm 0.29$ with $\chi^2_\nu = 0.79$), and indeed is poorly fit with the expected virial slope (for the $b = -2$ fit shown in the figure, $\chi^2_\nu = 3.71$, although more than 50% of the contribution to χ^2_ν is due to the single data point from 1996). Note that data from two years, 1993 and 1995, have not been included in this plot because the rms spectra for these two years have a strong double-peaked structure that we are unable to account for at present. We also note that a rather better relationship between the Hβ time lag and rms line width is found if we use the CCF peak rather than the centroid for the BLR size, as shown in Fig. 2b ($b = -1.47 \pm 0.21$ with $\chi^2_\nu = 0.59$, and for the $b = -2$ fit shown in the figure, $\chi^2_\nu = 1.58$). The CCF centroid represents the responsivity-weighted mean radius of the Hβ line-emitting region, but the CCF peak has no similarly obvious interpretation, though in some geometries the cross-correlation peak is a probe of the emission-line gas closest to the central source. In any case, the virial mass we infer from the mean of the Hβ data is the same within the uncertainties regardless of whether the CCF centroid ($7.3\,(\pm 2.0) \times 10^7\, M_\odot$) or peak ($6.8\,(\pm 1.0) \times 10^7\, M_\odot$) is used to infer the BLR size. There are a number of possible reasons for the large χ^2 values for the virial fits; it is important to remember that both the lag and line width are dynamic quantities that are dependent on the mean continuum flux, which can change significantly over the course of an observing season. We attempted to test this by isolating individual "events" in the light curves and repeating the analysis. Unfortunately, the relatively few spectra in each event significantly degraded the quality of both the lag and line-width measurements and thus proved to be unenlightening.

A diagram similar to our Fig. 1 was published by Krolik et al. (1991) for NGC 5548. We believe that our improved treatment, plus additional data, makes the case more compelling primarily because we measured the broad-line widths from the variable part of the spectrum only (i.e., the rms spectrum) rather than by multiple-component fitting of the broad-line profiles. Also, we included only lines for which we could determine both accurate lags and line widths in the rms spectra, thus excluding Ly$\alpha\,\lambda$1215 because of contamination by geocoronal Lyα in the rms spectrum, N V λ1240 because it is weak and badly blended with Lyα, and O I λ1304 on account of its low contrast in the rms spectrum. We excluded Mg II λ2798 because of its poorly defined time lag — the response of this line is long enough for aliasing to be a problem. Finally, we also included optical lines (Hβ and He II λ4686) not included by Krolik et al., plus additional UV measurements from the 1993 monitoring campaign.

An obvious question to ask is whether or not it is possible to *directly* determine the BLR kinematics by differential time delays between various parts of emission lines (e.g., in the case of purely radial infall, the redshifted side of an emission line should respond to continuum changes before the blueshifted side). In general, cross-correlations of emission-line fluxes in restricted Doppler-velocity ranges have failed to yield any significant time lags (e.g., Korista et al. 1995), consistent with, although not proving, the virial hypothesis.

3. Discussion

We have shown that the emission-line time-lag/velocity-width relationship argues very strongly for an SBH of mass $\sim 7 \times 10^7\,M_\odot$ in the nucleus of NGC 5548. The accuracy of this determination is limited by unknown systematics involving the geometry, kinematics, and line reprocessing physics of the BLR. As a simple illustration, we consider C IV λ1549 line emission from a BLR consisting of clouds in a Keplerian disk with radial responsivity proportional to $r^{-2.5}$ (which is steep enough to make the results fairly insensitive to the outer radius of the disk) and inner radius $R_{\rm in} = 3\,$lt–days. A relatively low central mass ($5 \times 10^6\,M_\odot$) with high inclination ($i = 90^{\rm o}$) disk and asymmetric line emission can fit the 1989 C IV results in Table 1. At the other extreme, a larger mass ($1.1 \times 10^8\,M_\odot$) is required for a lower inclination ($i = 20^{\rm o}$) and isotropic line emission. For further comparison, the specific model of Wanders et al. (1995), based on anisotropically illuminated clouds in randomly inclined Keplerian orbits, requires $M = 3.8 \times 10^7\,M_\odot$, and extrapolation to the BLR of the Fe Kα disk model of Nandra et al. (1997) requires $M = 3.4 \times 10^7\,M_\odot$.

As shown by Peterson et al. (1999), the Hβ emission-line lag varies with continuum flux, though as with the results discussed here, the correlation shows considerable scatter, probably because of the dynamic nature of the quantities being measured. But it seems clear that as the continuum luminosity increases, greater response is seen from gas at larger distances from the central source. We argue here that this also results in a change in the emission-line width; as the response becomes dominated by gas further away from the central source, the Doppler width of the responding line becomes narrower. This shows that the different widths of various emission lines is related to the radial distribution of the line-emitting gas — high-ionization lines arise at small distances and have large widths, and low-ionization lines arise primarily at larger radii and are thus narrower.

While this accounts for some important characteristics of AGN emission lines and their variability, it is nevertheless clear that this is not the entire story, as there is still scatter in the relationships that is unaccounted for by these correlations. As a further example, with central masses this large, some relative shifts in the positions of the emission lines are expected from differential gravitational redshifts. The gravitational redshift for each line in NGC 5548 is given by

$$\Delta V = \frac{GM}{cr_{\rm BLR}} \approx \frac{1160\,{\rm km\ s^{-1}}}{r_{\rm BLR}\,({\rm light\ days})}. \tag{1}$$

This clearly predicts that that high-ionization lines ought to be redshifted relative to the low-ionization lines, when in fact the opposite is observed (Gaskell 1982; Wilkes 1984). This might be due to incorrect subtraction of narrow-line components or, for example, by an optically thin component to the high-ionization lines (e.g., Shields, Ferland, & Peterson 1995) which will not necessarily appear in rms spectra and which may have a different velocity field than the optically thick component. Also, as noted earlier, in two of the eight years of optical data on NGC 5548, the Hβ profile in the rms spectrum is strongly double-peaked. We do not see an obvious explanation for why the emission line should be single-peaked on some occasions and double-peaked on others.

4. Summary

We have shown that in the case of the Seyfert 1 galaxy NGC 5548 emission-line variability data yield a consistent virial mass estimate $M \approx 7 \times 10^7\,M_\odot$, though systematic uncertainties about the BLR geometry, kinematics, and line-reprocessing physics limit the accuracy of the mass determination to about an order of magnitude. Data on multiple emission lines spanning a factor of ten or more in distance from the central source shows the $r_{\rm BLR} \propto V_{\rm FWHM}^{-2}$ correlation expected for virialized BLR motions. The time delay of Hβ emission is known to vary by at least a factor of two over a decade (Peterson et al. 1999), and we show here that the line-width variations are anticorrelated with the time-delay variations. The central mass is concentrated inside a few light days, which corresponds to about 250 Schwarzschild radii ($R_{\rm S} = 2GM/c^2$) for the mass we infer, which argues very strongly for the existence of an SBH in NGC 5548.

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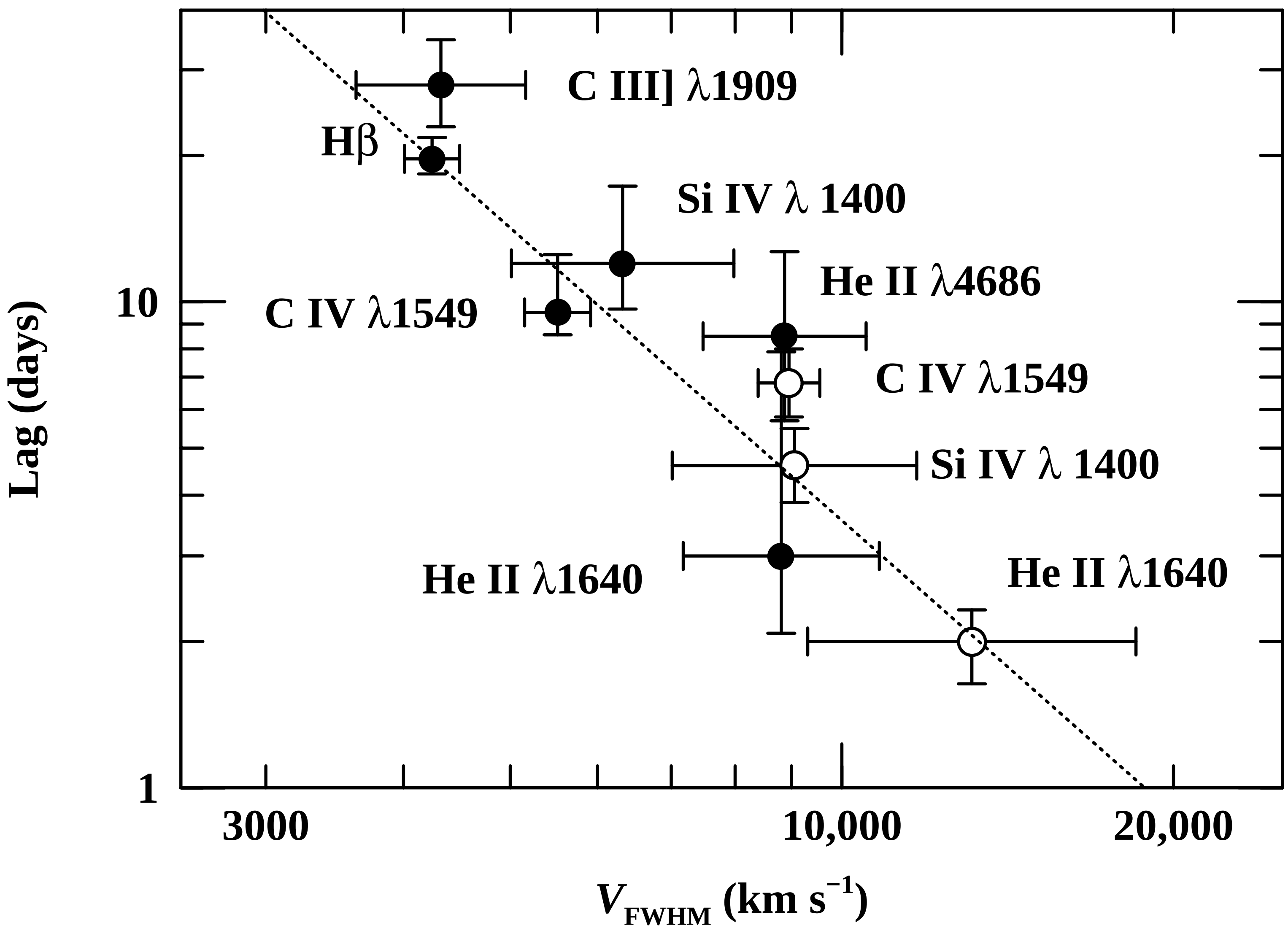
Fig. 1.— The time lags (cross-correlation function centroids $\tau_{\rm cent}$) in days (1 light day $=$ 2.6×10^{15} cm) for various lines in NGC 5548 are plotted as a function of the full-width at half maximum of the feature (in the rest frame of NGC 5548) in the root-mean-square spectrum. Points plotted are listed in Table 1. The filled circles refer to data from 1989, and the open circles to data from 1993. The dotted line indicates a fixed virial mass $M = 6.8 \times 10^7\,M_\odot$.

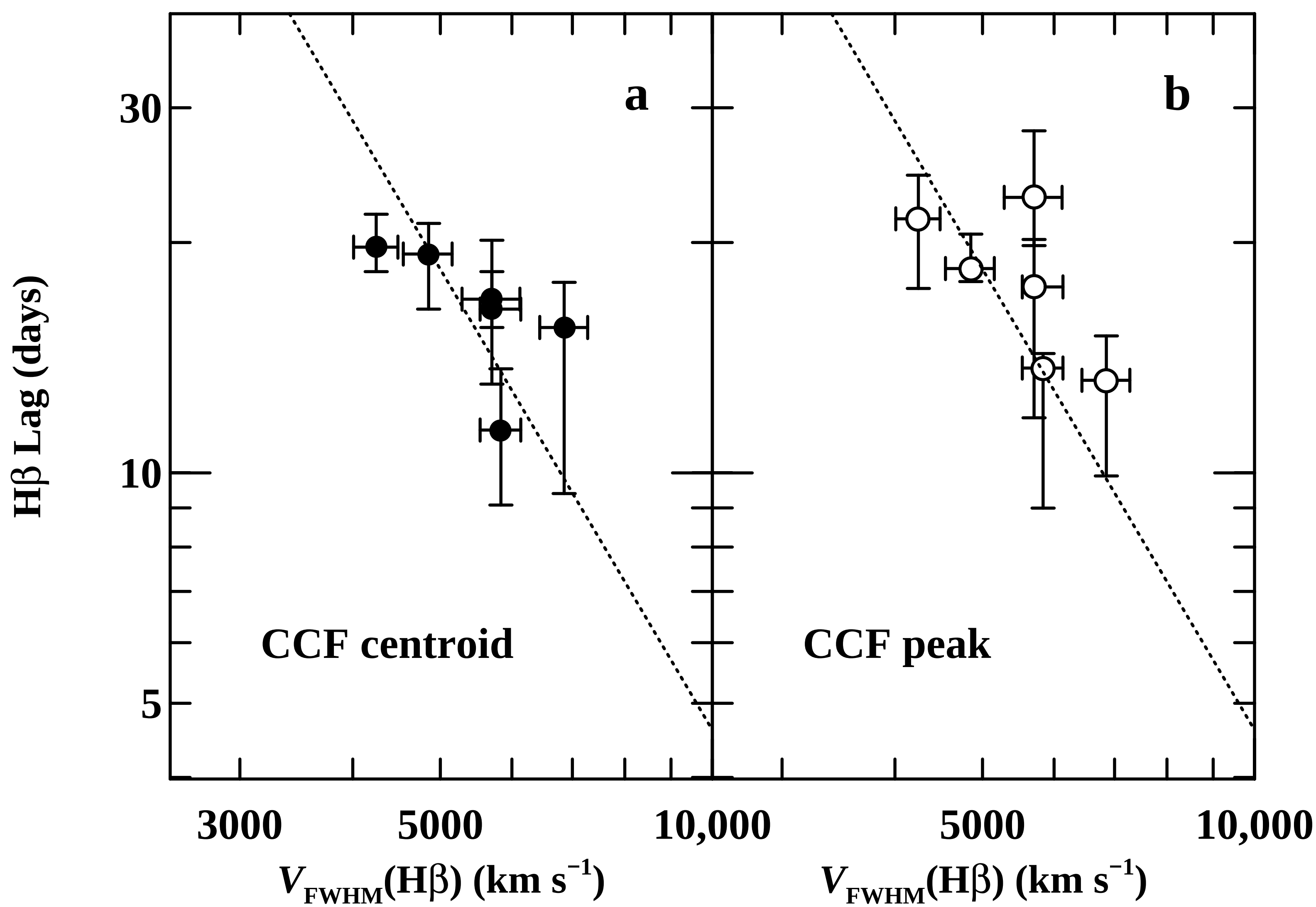
Fig. 2.— This plot shows six measurements (based on yearly averages) of the broad Hβ emission-line time lag and corresponding width of the Hβ feature in the rms spectrum formed from a homogeneous subset of spectra obtained during each year. In panel *a* (left), the time delay is based on the centroid of the continuum–Hβ CCF, and in panel *b* (right), the location of the peak value of the CCF is used. The dotted line corresponds to a fixed virial mass $M = 6.8 \times 10^7\,M_\odot$.

Table 1. Virial Mass Estimates for NGC 5548

Year (1)	Emission Line (2)	$\tau_{\rm cent}$ (days) (3)	$V_{\rm FWHM}$ (km s^{-1}) (4)	Mass ($10^7\ M_\odot$) (5)
1989	Si IV λ1400	$12.0^{+4.4}_{-2.6}$	6320 ± 1470	$7.0^{+4.2}_{-3.6}$
	C IV λ1549	$9.5^{+2.6}_{-1.0}$	5520 ± 380	$4.2^{+1.3}_{-0.7}$
	He II λ1640	$3.0^{+2.9}_{-1.1}$	8810 ± 1800	$3.4^{+3.6}_{-1.9}$
	C III] λ1909	$27.9^{+6.0}_{-5.5}$	4330 ± 770	$7.7^{+3.2}_{-3.1}$
	He II λ4686	$8.5^{+3.4}_{-3.4}$	8880 ± 1510	$9.8^{+5.2}_{-5.2}$
	Hβ λ4861	$19.7^{+2.0}_{-1.4}$	4250 ± 240	$5.2^{+0.8}_{-0.7}$
1990	Hβ λ4861	$19.3^{+1.9}_{-3.0}$	4850 ± 300	$6.6^{+1.0}_{-1.3}$
1991	Hβ λ4861	$16.4^{+3.8}_{-3.3}$	5700 ± 480	$7.8^{+2.2}_{-2.0}$
1992	Hβ λ4861	$11.4^{+2.3}_{-2.3}$	5830 ± 300	$5.7^{+1.3}_{-1.3}$
1993	Si IV λ1400	$4.6^{+0.8}_{-1.4}$	9060 ± 2320	$5.5^{+3.0}_{-3.3}$
	C IV λ1549	$6.8^{+1.1}_{-1.1}$	8950 ± 570	$8.0^{+1.6}_{-1.6}$
	He II λ1640	$2.0^{+0.3}_{-0.4}$	13130 ± 4500	$5.1^{+3.5}_{-3.6}$
1994	Hβ λ4861	$15.5^{+2.3}_{-6.1}$	6860 ± 420	$10.7^{+2.1}_{-4.4}$
1996	Hβ λ4861	$16.8^{+1.4}_{-1.4}$	5700 ± 420	$8.0^{+1.4}_{-1.4}$



Lag (days)
10
1
3000
10,000
20,000
V_FWHM (km s⁻¹)
C III] λ1909
Hβ
Si IV λ 1400
He II λ4686
C IV λ1549
C IV λ1549
Si IV λ 1400
He II λ1640
He II λ1640


a
b
CCF centroid
CCF peak
Hβ Lag (days)
30
10
5
3000
5000
10,000
5000
10,000
V_FWHM(Hβ) (km s^-1)
V_FWHM(Hβ) (km s^-1)